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Generating powerful ultraviolet beams with the world's largest laser

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Introduction

The National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL) will begin ignition experiments in the year 2010, ushering in a new era in high-energy-density physics research (ref 1). The primary missions of NIF include stockpile stewardship for national security, performing research for fusion energy and unfolding new regimes in basic and applied science. Spanning the length of two football fields and over 85% complete, the NIF will house 192 laser beams, each measuring 0.4 meters in aperture. During an ignition event, all 192 beams will simultaneously converge on a 10-meter-diameter target chamber holding a fusion target the size of a dime (Fig. 1). Implosions of the target work far better at shorter laser wavelengths, which generate fewer hot electrons that can pre-heat the fusion target fuel and make it harder to compress. As a result, the NIF is designed to operate at the third-harmonic wavelength of its Nd:glass amplifiers, and to deliver up to 1.8 million joules of ultraviolet energy to the target in a few billionths of a second. During an ignition shot, temperatures in the target will reach tens of millions of degrees and pressures will exceed one billion atmospheres, similar to conditions inside the Sun and stars. When completed, the NIF will be the largest ultraviolet laser in the world, and its performance has already surpassed energy records. In December 2005, 152 kJ of infrared energy was generated with only 8 beams, exceeding the highest infrared energies ever achieved on a fusion class laser.

NIF Final Optics

The NIF layout for a single beamline is shown in Fig. 2. Amplified 1.053 -um (1ω) beams from the laser are transported in 2 x 2 quad arrangements to the target chamber where final optics assemblies convert the frequency of each quad of beams to the third harmonic (3ω) and focus them onto the target. Each final optics assembly contains four integrated optics modules that incorporate: beam conditioning, frequency conversion, focusing, diagnostic sampling and debris shielding capabilities into a single compact assembly (Fig. 3). The fused silica final focus lens is a wedged design that provides color separation at the target via lateral dispersion. As beam pointing is adjusted into the chamber for different targeting scenarios, precision actuators are used to adjust lens focus and maintain absolute angular alignment of the frequency conversion crystals.

The NIF frequency converter is designed to give optimal performance at the design point of 1.8 MJ and 500 TW. Efficient operation at this level requires precise control of tolerances; crystals must be tilted to micro-radian accuracy, temperature must be controlled to a few hundredths of a degree, and wavelength must be set to a hundredth of an Angstrom. Crystal surfaces must also be finished to a nanometer smoothness so that the high-power 3ω laser pulse will have the required beam quality. The two types of crystalline materials used in the NIF frequency converters are potassium dihydrogen phosphate (KDP) and deuterated potassium dihydrogen phosphate (KD*P), both with dimensions of 42 × 42 cm. The KDP functions as a Type I doubler, and the KD*P is used for Type II tripling.

Third Harmonic Generation

Third harmonic generation for NIF is accomplished by a sequential application of collinear sum-frequency mixing in two nonlinear optical crystals (Fig 4). A beam at the fundamental laser frequency enters the doubling crystal in which two-thirds of the incident light is converted to the second harmonic frequency via degenerate sum-frequency mixing ($2\omega = 1\omega + 1\omega$). The co-propagating second harmonic and residual fundamental beams that emerge from the doubling crystal enter the tripling crystal, where a third harmonic beam is created by sum-frequency mixing of the fundamental and second harmonic beams ($3\omega = 2\omega + 1\omega$).

The efficiency with which energy is transferred from the fundamental wave to the harmonic waves is dependent upon a number of parameters, of which phase-mismatch is particularly important. Phase-mismatch is defined as the difference between the k-vector of the output wave and the sum of the k-vectors of the input waves. Maximum energy transfer from the input waves to the generated waves occurs when the phase-mismatch is zero. This condition is usually achieved in nonlinear optical crystals by using the birefringence of the crystal to balance the effects of normal dispersion. This leads rather naturally to two types of phase matching: Type I, in which the input waves have the same polarization inside the crystal, and Type II, in which the two input waves are orthogonally polarized (ref 2).

The NIF frequency converter employs Type I second harmonic generation followed by Type II third harmonic generation, a selection made on the basis of angular and polarization sensitivities and the sizes of the crystal boules needed to produce frequency converter plates of the appropriate size. In this scheme, the critical 2:1 mix ratio of 2w to 1w energy needed for efficient frequency tripling is achieved by angularly biasing the the Type I doubler a few hundred microradians from exact phase matching. As a result, the Type I / Type II design is more angularly sensitive than a comparable Type II/Type II design, but has the advantage of being quite insensitive to depolarization.

Crystal Growth and Fabrication

Over the past 10 years, technologies have been successfully developed to quickly grow large, high quality KDP crystalline boules to the sizes needed for fabrication of the optics needed for the NIF. The fast-growth method currently used for production of large, single crystal boules of KDP was pioneered in Russia and has been previously described elsewhere (ref 4). The large KDP crystals currently in use in the NIF were grown at LLNL and two commercial vendors: Cleveland Crystals Inc. (CCI) and the former Inrad, Inc. (now Photonic Products Group, Inc.). The 80% of the hydrogen is substituted with deuterium to minimize stimulated Raman scattering (~2x) from third harmonic generation (ref 5).

While the growth of crystal boules needed to produce NIF crystal optics can now be considered an established production process, the production of finished crystals to meet all NIF specifications is a relatively recent accomplishment. KDP and its deuterated analog are difficult materials to fabricate in the large aspect ratios required for NIF. The high water solubility of KDP requires non-aqueous processing. In addition, KDP is very thermally sensitive – a temperature change of ~2ºC is sufficient to induce fracture in the presence of a flaw <100 microns in size. Both faces of both crystals are SiO_2 sol-gel antireflection coated. The input and output faces of the doubler and the input face of the tripler are coated for maximum transmission at a wavelength of 700 nm, which provides very high transmission at both 1054 nm and 527 nm. The exit face of the tripler is coated for maximum transmission at 351 nm.

Performance

The frequency converted performance of the NIF laser has been tested and verified in a series of experimental campaigns referred to as NIF Early Light (ref 6). These campaigns, conducted between Nov 2002 and Sept 2004, included the first NIF target experiments utilizing one quad of beams on the target chamber, as well as detailed single-beam laser characterization experiments executed with the NIF Precision Diagnostic System (PDS). The PDS is a 6000 ft^2 facility inside the NIF building incorporating a single-beam version of the final optics assembly (one integrated optics module) and a comprehensive suite of input and output beam diagnostics that allow a far-more complete evaluation of the laser performance than can be achieved on the target chamber. A roving mirror assembly is used to select specific beams exiting the laser amplifier and direct them to the PDS for individual diagnosis.

The PDS campaigns successfully demonstrated 3ω operation at energy levels up to 10.4 kJ in a flat-in-time 3.5-ns pulse (equivalent to 2 MJ for full NIF, meeting the NIF 1.8-MJ design requirement). Frequency doubling was also tested by removing the tripling crystal and reducing the doubler tuning angle offset to ~120 μrad to better optimize the phase-matching for second-harmonic generation; 2ω energies up to 11.4 kJ/beam in a flat-in-time 5-ns pulse were produced in this configuration. Fig. 5 shows near-field images for the highest energy 2ω and 3ω shots, both demonstrating excellent beam quality at record harmonic energies from a single laser aperture.

Conclusions

The NIF experimental campaigns to date have demonstrated: 1) successful commissioning of one full quad of the 192-beam National Ignition facility laser all the way from the master oscillator through the frequency converter and to a target located at the center of the target chamber and 2) commissioning of two full quads (8 beam lines total) up to the switchyard producing world record energies up to 152 kJ at 1ω (ref 7,8). The NIF is expected to be fully completed in 2009, and experiments that utilize all 192 beams to the target chamber will begin in 2010. The missions of the NIF will enable the U.S. to be the first in demonstrating the extreme conditions of a fusion event within the confines of a laboratory and forging new scientific territory in the areas of astrophysics and high-energy-density science.

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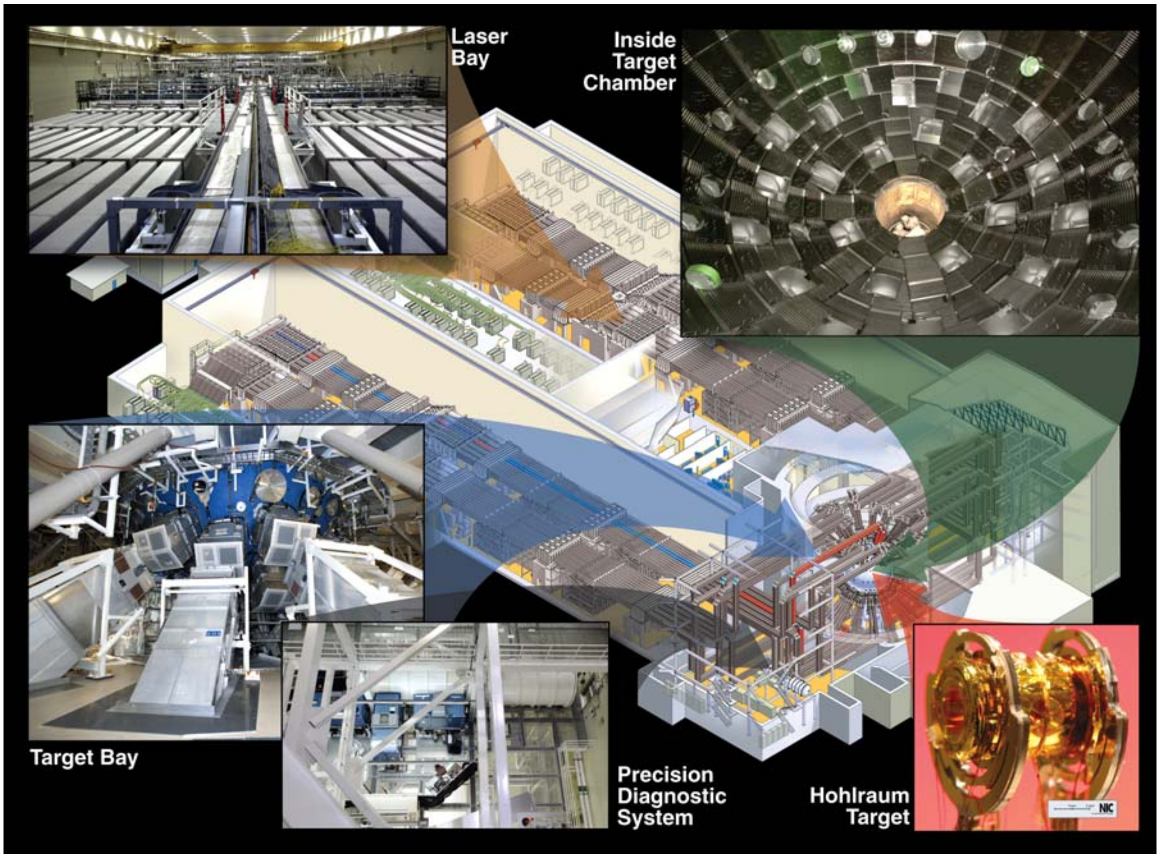

Fig. 1. This schematic of the 192-beam National Ignition Facility shows (clockwise from bottom left) the target chamber, laser bay, inside of target chamber, hohlraum target, and precision diagnostics system.

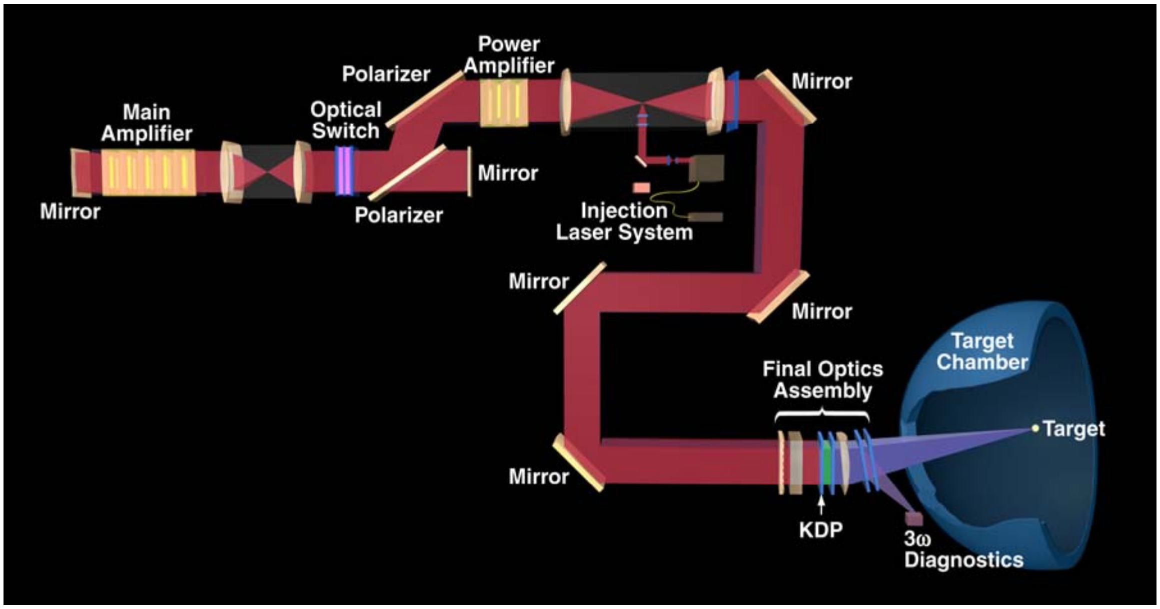

Fig. 2. To extract more laser energy per unit of flashlamp light and laser glass, the NIF utilizes a multi-pass amplifier. Light is injected into the transport spatial filter, traverses the power amplifiers, and then is directed to the main amplifiers, where it makes four passes before being redirected through the power amplifiers towards the target. To enable the multi-pass of the main amplifiers, a KDP-containing Pockels cell rotates the polarization of the beam to make it either transmit through or rotate off of a polarizer held at Brewster's angle within the main cavity. If transmitted, the light reflects off of a mirror and makes another pass through the cavity. If reflected, it proceeds through the power amplifier to the target.

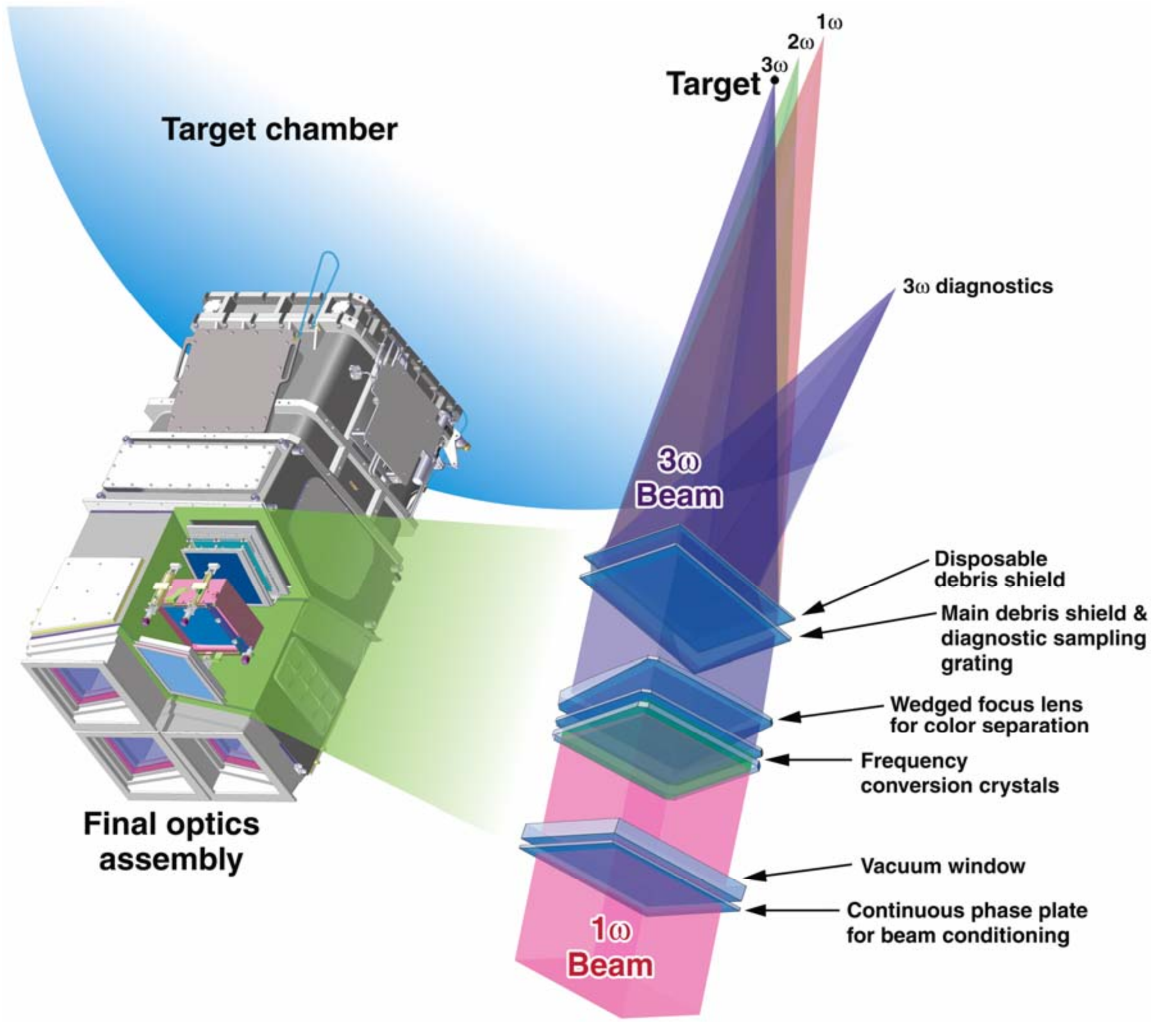

Fig. 3. The final optics assembly outside the target chamber contains: a phase plate (beam conditioning), KDP crystals (frequency conversion), fused silica lens (focusing), and two fused silica plates (debris shielding).

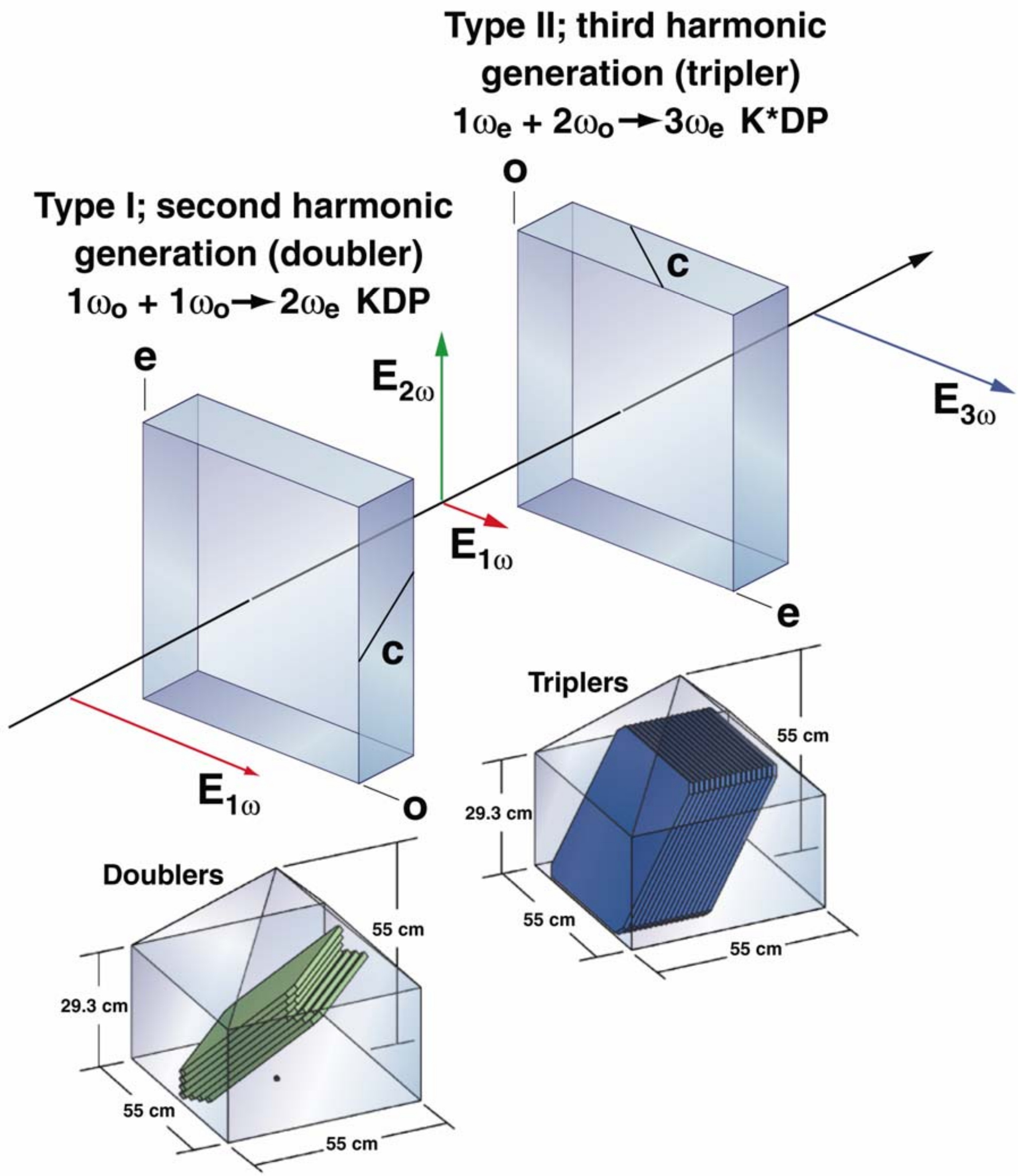

Fig. 4. Schematic of third harmonic generation for NIF with two different crystals. Type 1 second harmonic generation with KDP is followed by Type II third harmonic generation with KD*P. Beam polarization is shown in comparison to the crystalline c-axis.

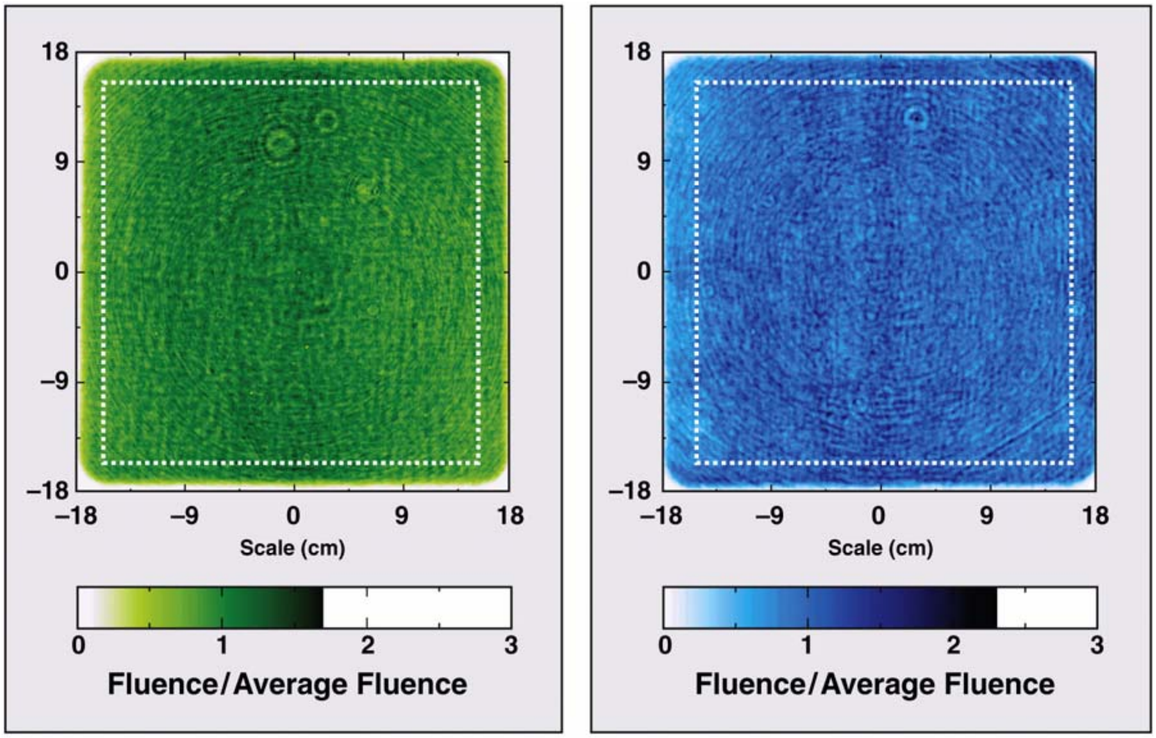

Fig. 5. Color enhanced near field beam images of high-energy 2ω (left) and 3ω (right) shots obtained in the NIF precision diagnostics System (PDS). The average contrast ratio (standard deviation of fluence/average fluence) within the outlined aperture for the 2ω beam is 0.13 and 0.17 for the 3ω beam.